Fabrication of Microstructures for Microphotonic Circuit

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ABSTRACT

We describe fabrication of sub-micron photonic bandgap structures on Si/SiO_2 optical waveguide, which could be used at $\lambda=1.54\mu m$.

INTRODUCTION

Control of the propagation of light using the photonic band gap (PBG) effect in photonic devices is the subject of intense international effort [1]-[6]. PBG materials are optical analogs of semiconductors. Main drive is towards making structures that modulate free photon dispersion as much as the same way as semiconductor crystal does for electrons. A high dielectric contrast material system is a fundamental requirement for the existence of a PBG. Silicon microphotonics, which uses Si over SiO_2 system, provides a large index difference ($\Delta n \approx 2.0 @ 1.54 \mu m$) between the core and the cladding of the guide. Because of the high confinement of the optical wave, the waveguide cross-section has been miniaturised. Strip waveguides with holes of 200nm diameter have been fabricated. The cross-section of the strip waveguide is 0.26×0.5 μm. We have addressed some of the important issues regarding fabrication. On the simulation front, we have used commercially available software Fimmprop3D for 2D simulation of the device. Figure 1(a) and (b) shows the simulation results. Actual structure is shown in the inset of Figure 1(b).

High index contrast structures introduce a process problem because performance is limited by scattering loss from surface roughness. One important challenge towards realizing silicon microphotonics lies in making optically smooth structure to keep the scattering loss as low as possible. The dominant source of loss is the sidewall roughness scattering [7]. The increase is attributed to sidewall roughness created during the waveguide patterning process involving lithography and RIE. We have proposed combined chlorine-fluorine based plasma as a reactive ion-etching recipe for silicon microphotonics. Extremely smooth photonic structures of feature size as small as $0.1\mu m$ have been made.

FABRICATION

PBG effect devices have been made using high-resolution lithographic and pattern transfer processes, which include electron beam lithography and reactive-ion-etching. The first step is the realisation of the plasma etch mask. The poor etch resistance of PMMA is serious limiting factor for pattern transfer. The problem has been overcome by using Al as a metal etch mask.
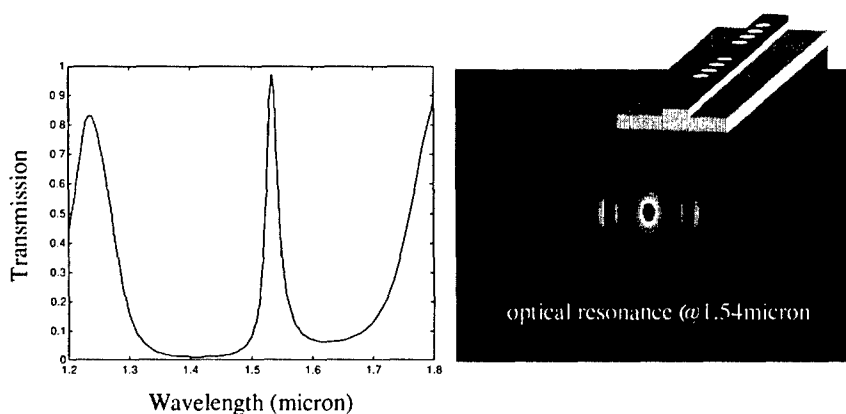
Wavelength (micron)

Figure 1. Simulation shows transmission for the waveguide microcavity structure designed for a resonance wavelength at 1.54 micron

In this work we have used Unibond silicon-on –insulator wafer (obtained from SOITEC, France), consisted of $0.26\mu m$ crystalline silicon layer on $1.0\mu m$ SiO_2 cladding layer on silicon substrate. . Direct-write electron-beam lithography with acceleration voltage of 60 kV, and 12nm spot size is used to generate the pattern in polymethylmethacrylate (PMMA) that has been spun at 7000 rpm and baked at $180^{0}C$ on to the silicon substrate. The PMMA thickness is typically 500nm. The exposed chip was then developed in 3:1 Isopropyl Alcohol and Methyl-Iso-Butyl-Ketone (IPA : MIBK=3:1) for 45 seconds at $25^{0}C$. The chip then undergoes 30seconds of oxygen plasma cleaning to remove any resist debris from exposed area.

Following the development a thin layer ~70nm Al has been evaporated, at 0.001mTorr pressure. Soaking the sample in acetone and dissolving the PMMA then lifts off Al. Normally the sample is left in Acetone overnight. Ultrasonic agitation for approximately 10-15 seconds is also required to remove the circular Al films. Successful lift-off results an Al mask directly on to the substrate. SEM image of a typical sample after lift-off is shown in Figure 2

.All RIE was performed on a STS 320PC parallel plate etcher operating at 13.56MHz. There are several plasma etching related considerations that can affect device performance. These include etch rates of Si and SiO_2 and their selectivity over Al, directionality of etching and surface damage.

Various gas combinations including CF_4/O_2, CF_4 $/O_2/CHF_3$, $SiCl_4/CF_4$ have been investigated to etch Si and SiO_2. Plasma of CF_4 with O_2 etches silicon at a rate 200nm/minute. Etch rate of oxide is rather slow. CHF_3 could be used to etch oxide. Etching oxide with CHF_3 has a profound influence on silicon sidewall. In fact one can move from isotropic to anisotropic etch by controlling the flow rate of CHF_3. Figure 2 (a) shows the undercut of silicon layer of SOI substrate during oxide etching.
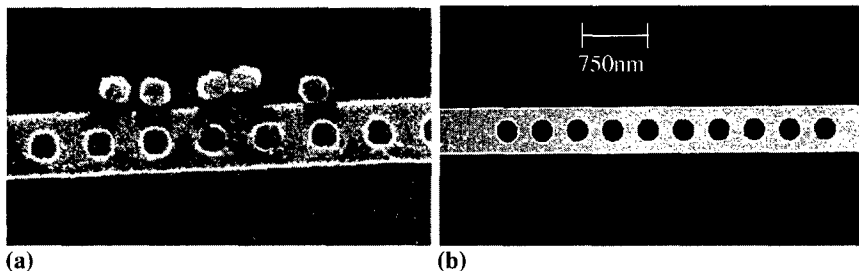
(a)   **(b)**

**Figure 2.** (a) Lift-off without any agitation, (b) Lift-off with 15 seconds of ultrasonic agitation

The CF_4 /O_2/CHF_3 plasma is of particular interest. Directional etching has been done with 5 sccm CHF_3, 8 sccm CF_4, 4 sccm O_2, at 2mTorr, 400W. These conditions were optimized to give a highly directional etch for silicon and oxide with an approximate etch rate of 150nm/minute. In such a plasma each gas has a specific influence to control the etch profile. CF_4 produces the F* radicals for the chemical etching of the silicon forming the volatile SiF_4. O_2 gives O* radicals, which passivates the silicon surface with SiO_xF_y and CHF_3 produces CF_x+ ions that removes SiO_xF_y layer by forming the volatile CO_xF_y at the bottom of the etched holes [8].

As far as directionality and etch rate is concerned $SiCl_4$/CF_4 plasma etching is another possible optimum etching process. It is quite well known to use $SiCl_4$ plasma for etching Si to achieve anisotropic silicon nanostructures. [9] Physical etching nature of chlorine-based plasma creates rough surface, sometimes-called "grass" effect, is unacceptable for photonic wire fabrication. Addition of CF_4 in the $SiCl_4$ plasma was found to reduce surface roughness or "grass" effect [10]. It is known that fluorine based etching of silicon is isotropic, while chlorine-based plasmas enable anisotropic etching because of sidewall passivation. These facts suggest that a chlorine-based plasma mixed with fluorine atoms could be used to form a user defined optimized profile. CF_4 produces F^* radicals as the dominant etching species. When clean silicon is exposed to atomic fluorine, it soon acquires "fluorinated skin". F atoms, after penetrating the fluorinated skin, attack Si--Si bonds, resulting in stable volatile end product SiF_4. $SiCl_x$ from $SiCl_4$ induces inhibitor type anisotropy when etching silicon[9].

A mixture of 20sccm $SiCl_4$ and 20sccm CF_4 have been used to perform etching at a pressure 20mTorr at 300W for 3minute 30 seconds on the SOI substrates.

Extremely smooth waveguide with holes of extremely good circularity have been found, which clearly put this etching recipe as a strong candidate for silicon microphotonics fabrication. The CF_4/$SiCl_4$ system is one member of a family of etching mixtures that can be used to etch silicon anisotropically via the inhibitor mechanism. Another possible combination would be $SiCl_4$/CHF_3 at 10mTorr, 300W. Manipulation of the feed mixture composition can be used to adjust the profile contour and degree of anisotropy.

Following the etching, the Al is removed with a wet etch. Optical facet production is the next important step for the strip waveguide. Unfortunately silcon doesn't cleave easily. Yu *et al* [11] have successfully cleaved (100) silicon by thinning the silicon substrate to $90\mu m$
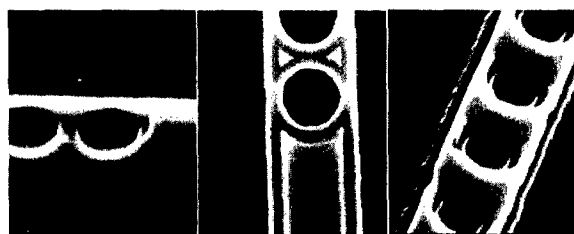
(a)
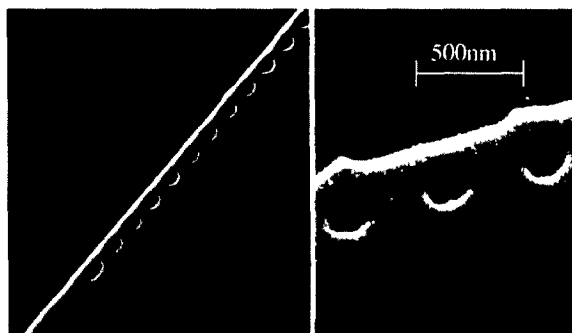
(b)

(c)

Figure 3 Scanning electron micrograph of $\lambda=1.54\mu$m PBG waveguide. (a) Effect of CHF$_3$ on silicon sidewall. (b) Device made by CF$_4$/O$_2$/CHF$_3$ plasma. (c) Device made by CF$_4$/SiCl$_4$ plasma.

before cleaving. We have designed a special tool to cleave unthinned (100) silicon substrates. A typical sample after cleaving is shown in Figure 4.
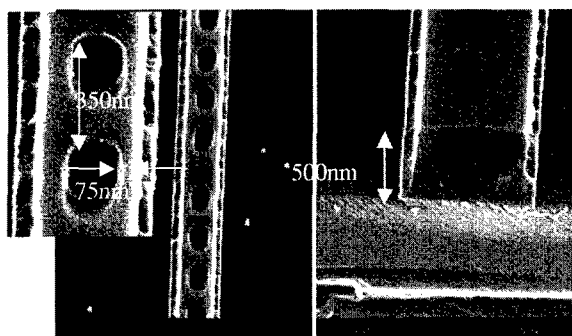
Figure 4 Scanning electron micrograph of a 1D optical cavity and of cleaved end face of λ=1.54μm PBG waveguide.

CONCLUSIONS

In conclusion, a process has been described for fabricating smooth grass free structure on Unibond SOI material for use in silicon microphotonics circuit. A lift-off mask mask of Al and combined chlorine-fluorine based plasma as a reactive ion-etching recipe were used to make the structures. Optical probing of the structure to measure loss characteristics and band-gap behavior is under progress.

ACKNOWLEDGEMENTS

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